

SPECIAL CONSIDERATIONS IN APPLYING POWER LINE CARRIER FOR PROTECTIVE RELAYING

IEEE Power Systems Relaying Committee

Special paper

Relaying Communications Subcommittee
Working Group H9

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Introduction

Power line carrier has been applied to power lines in this country for over 80 years. In 1919, the first system for voice-communication purposes was placed into service. By the late twenties, power line carrier was used for pilot protective relaying, and has continued to provide this service ever since. [B66]

With the explosion of fiber and the high bandwidth communication, many engineers surmise that Power Line Carrier is a dying technology. To the contrary, as leased lines become difficult to acquire and fiber optic channels expensive to install, Power Line Carrier is still the most economic channel for dedicated protective relaying available. The media is readily available – the power line itself. With the addition of a line tuner, the CCVT (used for potential input to the protective relay) can be used to couple the PLC signal to the power line. If the only communication channel required is for protective relaying, then Power Line Carrier is the obvious choice. Of course, maintenance costs should also be considered when determining the type of channel to use. Some PLC maintenance will require taking the transmission line out of service.

The goal in using communications for protective relaying is to provide simultaneous high-speed clearing for all faults within a line section, including end-zone faults. A PLC channel can also be used to provide remote tripping functions for transformer protection, shunt reactor protection and remote breaker failure relaying.

There are many references available that discuss PLC applications. IEEE 643 IEEE Guide for Power-Line Carrier Applications is a particularly good reference. In the bibliography section of this paper, many other references are listed.

The intent of this paper is not to cover the actual channel application but circumstances that can affect the performance of the protective relay system. Subjects such as a non-homogeneous line, the use of capacitors and reactors in the line, transformer-tapped lines, special protection applications, and the issue of non-licensure of PLC by the electric utility are covered. The intent of this paper is to document important issues that should be considered when applying a PLC channel to a protective relay system.

Special Considerations in Applying Power Line Carrier for Protective Relaying

Optimal Transmitter / Receiver Signal Levels

An optimal PLC channel would be a two terminal line with a high impedance (i.e. 1500 ohm) adjustable wide band trap at each end with enough bandwidth to block two pilot schemes and with line tuners that perfectly matched the 50 ohm carrier equipment to the characteristic impedance of the line. This system would have zero reflected power and would only have the series line attenuation to reduce the signal to the remote end. Real life in the Power Line Carrier world is not like that. We are faced with discontinuities in the line construction, which presents a change to the characteristic impedance, lines with cable segments, tapped power transformers, three terminal lines, and limited trap bandwidth at the geometric mean frequency (GMF), as well as line tuner matching that is a compromise.

The line trap is a tuned circuit that presents a high impedance to carrier frequencies and a low impedance to the 60 Hz power frequency. If the trap impedance is identical to the characteristic line impedance of approximately 377 ohms and assuming that the station bus impedance is very low, under normal conditions there will be a 6 dB loss to the carrier signal due to half the carrier signal current traveling through the trap into the system behind the protected line. If the trap impedance is higher, more of the signal will travel to the lower impedance line segment and eventually to the remote receiver.

The most important function of a line trap is to prevent the carrier signal from being diverted into the fault on the out-of-zone line or bus section. If there was a line to ground fault on the bus behind the protected line segment on the phase the carrier is applied, most of the signal would be shorted to ground and the signal level would not be adequate at the remote end. On a directional comparison blocking scheme, this would result in a remote end over-trip. With a line trap between the fault and the injection point, the carrier signal would see the trap impedance in series with the fault and the fault would have little or no affect on the carrier signal level. Another function of the trap is to isolate the protected line from system changes that are in other areas and not directly on the protected line. It should isolate any impedance changes due to line and bus switching as well as when protective grounds are connected to the high voltage system. It is common practice to install wave traps at each end of a two terminal line.

Three Terminal Lines

It is a recommended practice to install line traps at all three ends of a three terminal line. This will prevent faults or discontinuities external to the line section from attenuating the carrier signal transmitted to the remote ends. With the lines terminated into a line trap, reflected power will be kept to a minimum.

Tapped Transformers

A transformer tapped to a line using a PLC channel for communications may cause attenuation to the signal for several different reasons. The length of the tap line to the transformer may be near the quarter-wavelength of the carrier, the transformer may present either a low or high impedance to the signal which will create a reflected signal that will interfere with the main line signal, or the transformer may even present a short circuit to the carrier signal.

Quarter Wavelength Spur – When a tap line is not terminated into tuned carrier equipment or is terminated into a power transformer, and is one quarter wavelength of the carrier frequency in length or odd multiples thereof, the maximum out-of-phase reflected signal will occur. This reflected energy will be out of phase with the transmitted signal and can cause cancelation of the transmitted signal. To minimize this effect, line traps should be placed as close to the main line as possible. The trap will attenuate the signal traveling into the tapped line as well as the

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reflected energy returning from the tap section. The amount of isolation will be dependent on the trap impedance with respect to the impedance of the main line. The higher the trap impedance, the greater the signal attenuation will be.

Grounded Wye Connected Transformer – Transformers with a grounded wye connection provide a shunt path through interwinding and terminal to ground capacitances for the carrier signal to ground. This type of connection will greatly effect the levels of the carrier signal. A trap would usually be necessary when adding a tapped transformer with a Grounded Wye connection.

Delta Connected Tapped Transformer – Generally it has been found that delta connected transformers will have less attenuating effect on the carrier signal than grounded wye connections. Experience has shown that in some instances as many as three or four tapped transformers may be added to a line section before the attenuation becomes so great that the remaining signal is too low to be usable. The characteristic impedance of transformers can vary greatly and is difficult to determine. A trap installed close to the main line will usually reduce the attenuation effect caused by delta connected tapped transformers.

Some interesting results were found and described in a paper “Carrier Frequency Characteristics of Power Transformers” written in 1951 [B152]. It was determined that approximate capacitances at carrier frequencies between terminals and from terminals to ground in power transformers could be calculated from data obtained by actual transformer measurement. Measurements and calculations showed that two winding transformer terminal to ground capacitive reactance is almost twice as high as the terminal to terminal capacitive reactance for both delta connected and wye connected transformers. Of the ten power transformers that were analyzed, the severest problem was caused by a 15,000 KVA 69 kV delta-wye transformer which attenuated a phase to ground carrier channel by 7 dB. Another interesting point was that the 115 kV wye-delta transformers that were analyzed attenuated a line to ground carrier channel by only 1 – 2 dB. Some of the conclusions drawn by the findings of this paper are:

1. Two-winding high-voltage power transformers in general present capacitive reactances of medium to high Q between high-voltage terminals and from high-voltage terminals to ground at frequencies in the power-line carrier spectrum. High-voltage autotransformers may exhibit resonance characteristics at frequencies within the carrier spectrum, particularly at the lower end, and hence may present shunt inductive or capacitive reactances at carrier frequencies.
2. The shunt capacitive reactances presented by high-voltage transformers may be sufficiently low at frequencies within the carrier band to cause appreciable losses due to reflection in otherwise clean carrier circuits. The higher the frequency used, the lower the shunt capacitive reactance.
3. It is feasible to calculate the approximate capacitances at carrier frequencies between terminals and from terminals to ground of a power transformer by the methods commonly used in calculating surge voltage distribution.

Line Configuration Changes

On any power system, many overhead transmission lines exist that are not uniform from one end to the other. This may be the result of separate lines with different design standards being joined, right-of-way needs dictating physical changes to the structures, sections being replaced or repaired that don't follow original design standards, sections of mutual right-of-way with other lines, or transpositions in the line conductors. The result is a line made up of segments where

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the conductor size may change, the relative configuration of the conductors may change, mutual proximity to other lines may exist, or various combinations of these situations. In the analysis of power line carrier signals, these changes represent discontinuities on the line. PLC signal loss due to these discontinuities may be significant and should be calculated in order to determine carrier performance.

Transpositions

The position of each phase in the geometry of a particular transmission line affects the mutual parameters of each phase. To more evenly balance the effects, the position of each phase is exchanged with the other phases periodically in a process known as transposition. A fully transposed line is one where each phase occupies each position approximately one third of the length of the line. Three transpositions are required to fully transpose the line and end up in the original configuration. Although transposing a line is desirable for balancing current on phases at the power frequency, it has negative effects on carrier signal strength. At carrier frequencies, a transposition represents a transparent discontinuity. "Transparent" means that the signal passes without reflecting back to the source. When analysis of the mode parameters is performed, it is revealed that the transposition causes a conversion of the modes initially from a signal that is primarily mode 1 to include mostly mode 2 and some mode 1. The resulting shift in modes causes a loss that can be as great as 6 dB. This is due to the higher attenuation of mode 2. If the next transposition occurs before mode 2 has attenuated, an additional loss of 2 dB can occur. If all three transpositions were to occur close enough to avoid much attenuation, the phases and the modes would be restored to their original configuration and the losses would be small [B131]

Non Homogenous Lines

Non-homogenous power line configurations present special PLC applications problems. One of the major problems is signal attenuation. An example of non-homogenous configuration is a transmission line that consists of part overhead conductor and part under ground power cable. Although an underground transmission line may be homogenous, it is also discussed here since the same attenuation problems exist when applying PLC to power cables.

At PLC frequencies, the characteristic impedance of underground cables and overhead conductors differ significantly from the values calculated at the power frequency. Because of this difference, an additional attenuation of the PLC signal will exist at each point where there is a transition from cable to overhead line or vice versa. The signal loss due to the discontinuity can be approximated by:

$$dB\ Loss = 20\text{Log} \left[\frac{(Z_1 + Z_2)}{2\sqrt{Z_1 Z_2}} \right]$$

Z1 and Z2 are the characteristic impedances of the power cable and the overhead line respectively.

Using typical characteristic impedances, (overhead line equal to 300 ohms and power cable equal to 30 ohms) the carrier signal loss at each discontinuity can be approximated at 6 dB.

Before applying PLC to any non-homogenous line configuration or to a power cable the total channel attenuation must be calculated or a reasonable approximation made. These calculations should be made using values that provide the maximum possible signal loss.

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The maximum allowable attenuation is dependent on the PLC receivers used at the transmission line terminals. The attenuation limit (channel attenuation rating) should be supplied by the equipment manufacturer. Generally, this rating is 40 to 45 below the transmitter rated output.

The typical carrier signal level operating margin is 15 to 20 dB. If the difference between receiver attenuation limit and line attenuation is 15 to 20 dB then the line is acceptable for power line carrier communication. A lower operation margin, less than 15 dB, can be used if the increased risk of a mis-operation can be accepted.

The PLC transmitter output signal can be amplified to increase the reliability of a marginal PLC channel where line length or discontinuities cause high signal loss. A 100-watt amplifier can be used to add 10 dB to the operating margin as long as care is taken to insure that the ratings of the line tuning equipment are not exceeded. The additional amplification can be beneficial even on short lines that have a single major discontinuity such as an overhead-underground connection.

When applying PLC to transmission lines with overhead – underground discontinuities the carrier frequency must be chosen so that the location of the discontinuity is not at a multiple of a quarter wave length of the carrier frequency. Lower PLC frequencies are preferable when underground cable is part of the carrier path. The following table shows the typical power cable losses at different carrier frequencies.

Frequency (kHz)	dB/mile Attenuation
30	2 – 3
40	2.5 – 3.5
50	3 – 4
100	6 – 8

Additional signal operating margin can be obtained by using extra high C coupling capacitors (0.02 microfarads). They will reduce resistive losses and increase the bandwidth thus reducing over all channel attenuation.

Another alternative is bypassing the PLC signal around the discontinuity to reduce PLC channel losses. This requires additional coupling capacitors and wave traps and may be cost prohibitive.

If an acceptable operating margin cannot be obtained after reviewing all of the above methods then an alternative protection scheme should be considered.

Basic Installation

Below is shown a typical end of a simple line terminal with the PLC equipment [B144].

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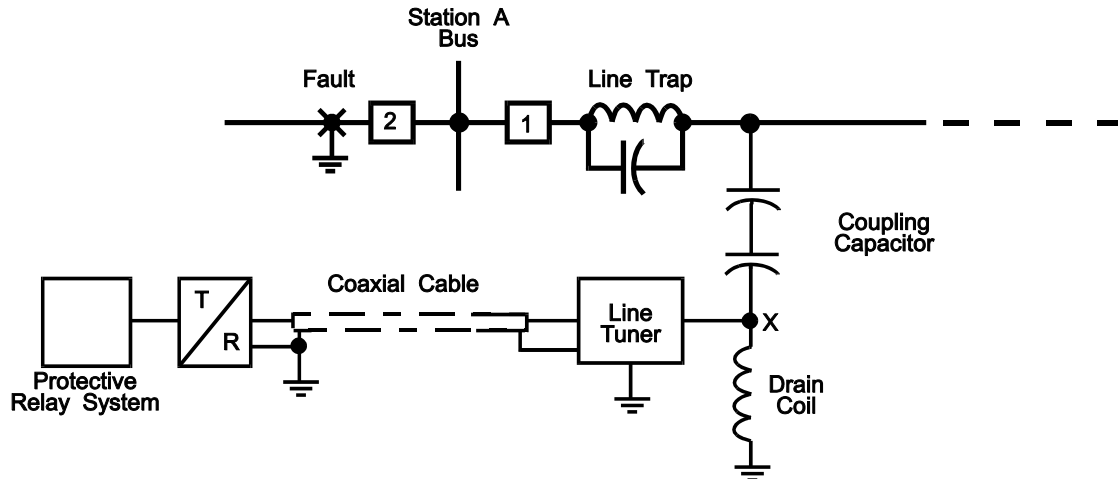


Figure 1 Basic Power Line Carrier Terminal

In this figure, it can be noted that the transmitted signal goes from the T/R transmitter via the coax cable to the line tuner, and then via high voltage lead in wire from the tuner to the coupling capacitor device which couples the signal into the transmission line. Conversely, the received signal reverses this path and arrives at the receiver of the T/R set.

The system, and therefore the application, can be impaired if a few basic installation steps are violated.

1. The coax cable should only be grounded at the T/R end and not at both ends. Grounding both ends will result in fault currents being introduced into the shield and either swamping the carrier signal, overloading the shield current carrying ability and resulting in cable damage, and/or GPR effects upon the signal and damaging the cable.
2. The cable from the tuner to the ccvt should be high voltage lead in wire rather than coax to avoid the losses that would occur, as well as insulation failures (typically 5kv insulation or higher).
3. The protective gaps in the ccvt, line tuner, and T/R (some older units) need to be set properly.

Coordination Of Protective Gaps

Typically, the manufacturers of each individual piece of equipment (tuner and ccvt) would specify a nominal gap based on maximum voltage limitation for the equipment. These gaps have to protect the equipment while at the same time if set too tight could result in gap flashover which would cause loss of carrier signal. These gaps may be open fixed, open adjustable, or some form of gas tubes.

It should be noted that some coordination of the gap settings may be desired. When one considers the maintenance and safety issues related to energized equipment up in the air, the gap coordination between the tuner and ccvt is something to consider. The typical location of the tuner should be below the ccvt but accessible from the ground level. This lends itself to having its gap set slightly smaller than the gap in the ccvt. The theory here is that the smaller gap will tend to fire more often than the wider gap. The gap in the tuner would be considerably easier & safer to inspect, adjust and clean, or repair down on the ground than the gap located inside the ccvt where it is much more difficult to access. The personnel would have a higher safety concern to even inspect the gap in the ccvt.

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For example, a typical gap setting is for the ccvt to have a gap setting of 0.0295 cm (0.075 inch), and the tuner to have a gap setting of 0.0197 cm (0.050 inch) for spark gaps or 0.01 – 0.0138 cm (0.025 - 0.035 inch) for disc gaps.

PLC Applications to Short Lines

When applying power line carrier to a short line, where line attenuation may be only 1 to 2 dB, care must be taken to insure that the power line carrier operates properly. When both the local and remote transmitters are on, the local transmitter may experience high VSWR (Voltage Standing Wave Ratio). This situation frequently occurs in electromechanical and some microprocessor relay Directional Comparison Relaying (DCR) schemes. Depending on the manufacturer, a VSWR protection circuit designed to shut down the local transmitter may be part of the design. If this protection is removed, or is not present, the local transmitter or other power line carrier electronics could be damaged. If the local transmitter shuts down, the remote terminal may "overtrip".

Following are two possible solutions that may help to avoid this problem:

1. Use a higher RF frequency. Generally speaking, use of higher RF frequencies on short power lines makes very good sense. Higher losses (in order of 3 to 6 dB) can be quite easily tolerated on short lines, and frequencies over 250 kHz are attenuated 2.5 times more than 100 kHz frequencies. Selection of higher frequencies will free up lower frequencies for use on adjacent longer line segments. It is also less expensive to connect PLC equipment operating on higher frequencies to a power line: costs of line traps, coupling capacitors and line tuners are considerably lower.
2. Reduce output power. Reduction of transmitter power output to a lower level will solve the transmitter alarm problem. Care must be taken that the transmitter spurious and harmonic output stays within the specification limits when the transmitter power output is set to some lower value. The equipment manufacturer should be consulted before making this adjustment.

Typical frequency stability of an on-off carrier set is ± 10 Hz, thus carrier beating occurs if local and remote carrier sets are set to the same frequency and line attenuation is low. The beating of the local and remote carrier frequencies produce a third frequency pulsating in amplitude between addition and subtraction of the frequencies. Because the Power Line Carrier can be cancelled, carrier beating may impair DCR schemes when carrier is keyed from both ends at the onset of a system fault. To avoid carrier cancellation on short lines apply the same solution used on multi-terminal lines by offsetting the local and remote frequencies by 100 Hz.

Proper Impedance Matching

Line tuners are utilized to compensate for the considerable impedance mismatch between the carrier equipment and power line. Incorrect connections of the line impedance matching transformer in the line tuner (line matching unit) will cause further impedance mismatch. The result is a high-reflected signal being fed back to the transmitter output, adding its voltage to the transmitter output voltage and possibly causing damage. This particular condition could exist on a power line of any length. Line tuners are typically shipped from a manufacturer with the line-matching transformer connected for 50 (or 75) ohms on the equipment side and 300 ohms on the line side. If the line impedance is considerably different from 300 ohms, a mismatch will occur. Changing the line tuner settings to match the equipment and line impedances will usually solve this problem.

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Similar high return voltage at the transmitter terminals may exist if the transmitter is connected to the line tuner through a LC tuned circuit. If the LC circuit presents more than 0.5 dB loss to the transmitter signal, its series impedance may be as high as 20 Ohms. This impedance, when added to the impedance of the coupling circuitry, will present higher load impedance to the transmitter output, thus causing mismatch and a high-reflected signal. Re-tuning the LC filter to the correct frequency should solve this mismatch problem.

Frequency Spectrum and Conservation

As more transmission lines are added and as old lines are broken up by addition of new buses and breakers in the line, the requirements for additional carrier frequencies is increasing. Where there is already considerable use of carrier, the availability of these additional frequencies is often limited unless line traps and perhaps carrier coupling equipment is replaced with components with a broader frequency capability.

One way to conserve the frequency spectrum and perhaps still be able to use the existing carrier coupling equipment is to utilize carrier transmitters and receivers that share a common channel. Where a Directional Comparison Unblocking /POTT scheme and DTT scheme is utilized on a line, a common guard frequency can be shared between the two systems. The likelihood of both systems being called on simultaneously is small and when it does occur, the higher priority system (normally the DTT) takes precedence. The advantage of this system is that for each terminal that requires both signals, one frequency is eliminated. Thus, on a three terminal line, up to three frequencies are available for use elsewhere on the system. The disadvantage of such a scheme is that loss of the shared guard channel will disable two systems. Where the recommended dual channel DTT with single channel fallback is used for security, the DTT system will remain intact on the second channel albeit not as secure. Another advantage of the shared channel is that fewer transmitters mean fewer hybrids, which translates into more of the transmitted signal being coupled to the line. The shared channel is an attractive alternative to adding another independent channel for communications.

An additional option to allow closer spacing of frequencies is to use a narrow bandwidth blocking carrier. This allows closer spacing of blocking carrier frequencies as compared to the standard bandwidth carrier. The disadvantage of the narrower bandwidth is that the operating speed is generally decreased. The slightly slower speed may be critical where stability system margins are small. This needs to be evaluated by the user.

Use of PLC at 250 kHz and above

The vast majority of power line carrier systems in use today operate at frequencies below 250 kHz. As the frequency spectrum becomes more congested, use of frequencies above 250 kHz has increased.

When considering use of frequencies above 250 kHz, several factors must be taken into account:

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1. Signal attenuation on power line at frequencies in the 250 kHz to 500 kHz range is higher than at lower frequencies. Following graph was extrapolated from Relaying Communication Channels, Application Guide (Reference B139) page 2-31 to cover attenuation versus frequency information for frequencies over 300 kHz.

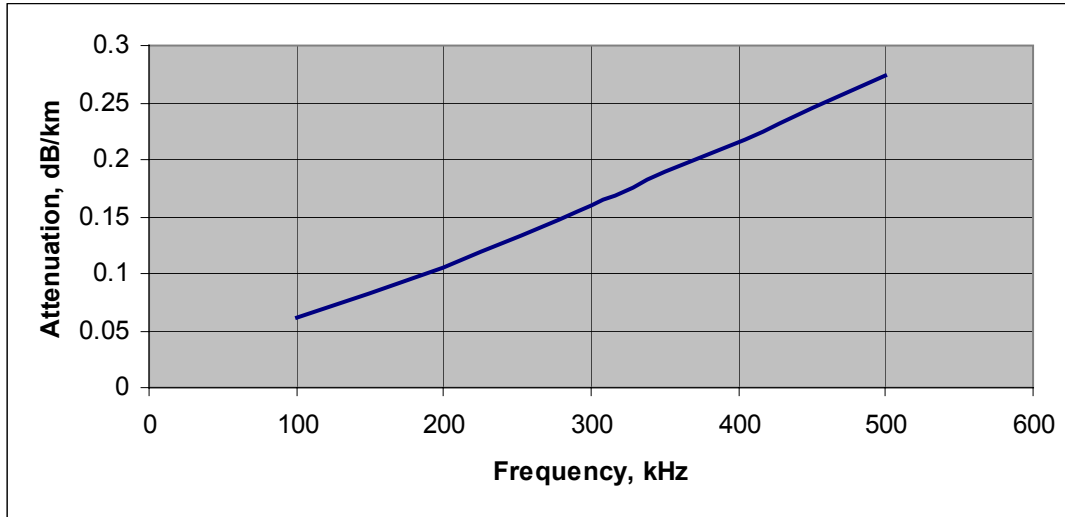


Figure 2 Signal Attenuation

2. Noise level generated by power lines is lower at frequencies above 300 kHz as shown on the following table. The table was extrapolated from the graphs on page 2-34 of reference B139.

Range of Transmission Line Noise Levels (3 kHz Bandwidth)

Power Line Voltage in kV	Frequency kHz	300	350	400	450	500
34.5 - 161	Fair Weather	-42 to -47	-43 to -48	-44 to -49	-45 to -50	-46 to -51
	Adverse Weather	-25 to -30	-26 to -31	-27 to -32	-28 to -33	-29 to -34
230- 345	Fair Weather	-37 to -42	-38 to -43	-39 to -44	-40 to -45	-41 to -46
	Adverse Weather	-20 to -25	-21 to -26	-22 to -27	-23 to -27	-24 to -28
500	Fair Weather	-35 to -40	-36 to -41	-37 to -42	-38 to -43	-39 to -44
	Adverse Weather	-15 to -20	-16 to -21	-17 to -22	-18 to -23	-19 to -24
765	Fair Weather	-27 to -32	-28 to -33	-29 to -34	-30 to -35	-31 to -36
	Adverse Weather	-7 to -12	-8 to -13	-9 to -14	-10 to -15	-11 to -16

3. Coupling devices, line traps and line tuners, required to couple PLC signals to a line in the 250 to 500 kHz band are less costly as compared with similar devices for lower PLC frequencies. A fixed wide band line trap with an inductance of 0.1 mH is sufficient to provide blocking of the 250 - 500 kHz band at 400 ohms impedance and its cost is approximately 30 % lower than a 0.265 mH line trap. Similarly, a wide band line tuner may be 15% less expensive, and provide coupling of the 250 – 500 kHz band using a coupling capacitor value of 3,000 pF or larger.

Special Considerations in Applying Power Line Carrier for Protective Relaying

4. When planning a PLC system, a frequency co-ordination with local airport beacons must be carried out. Airport beacons are licensed users of this frequency band and PLC signals must not interfere with these users.
5. Following assumptions were made in calculating maximum line length that would permit reliable operation of a PLC system:
 - A. Simplified formula for line attenuation was used (page 2-31 [B140])
 - B. Signal attenuation per miles was extracted from Figure 2 above
 - C. Line-voltage multiplier for adverse weather condition was used (page 2-31 [B140])
 - D. It was assumed that no transpositions exist on a line
 - E. 2 dB was allowed for coupling correction, with phase to ground coupling assumed
 - F. Line length for On-Off PLC system was calculated assuming 10-watt transmitter power output (+40 dBm), -5 dBm receiver sensitivity and 15 dB receiver margin
 - G. Line length for FSK PLC system was calculated assuming 1-watt guard transmitter power output (+30 dBm), -24 dBm receiver sensitivity and 20 dB receiver margin

Results of these calculations are shown in following tables:

Line length in kilometers for On-Off PLC carrier

Frequency in kHz	Line Voltage in kV					
	69	115	138	230	345	500
300	95	103	114	174	190	251
350	83	90	100	153	166	220
400	71	77	85	131	142	189
450	64	69	76	117	128	169
500	56	61	68	104	113	149

Line length in kilometers for FSK PLC carrier

Frequency in kHz	Line Voltage in kV					
	69	115	138	230	345	500
300	109	118	131	199	217	287
350	95	103	114	174	190	251
400	81	88	97	150	163	216
450	73	79	86	134	146	193
500	64	70	77	118	129	171

6. The Signal to Noise ratio (S/N) should not be an issue in the frequency range from 300 kHz to 500 kHz since the line noise is considerably lower in this frequency band when compared with receivers sensitivities.

Special Considerations in Applying Power Line Carrier for Protective Relaying

Single-sideband (SSB) Power Line Carrier

Single-sideband power line carrier is characterized by its multifunction capability. Pilot relaying can be applied through the use of voice channel or baseband equipment. Other telecommunication functions such as voice communication, telemetering, data acquisition, supervisory control, and automatic generation control can also be applied over the SSB system.

A single-sideband system may use keyed carrier blocking and frequency-shift transfer-trip channels for line protection. Although functionally the same as for any single-function application, single-sideband equipment does require different application practices. For example, SSB allows the choice of either the baseband or an audio channel to accomplish the relaying function. A SSB relaying channel shares the power output capability of the amplifier with other functions. Because the power amplifier is shared, the power available per channel is inversely proportional to the square of the number of channels applied on a given SSB system. Also, effective transmitter power levels must be calculated for the channel loading to determine the proper application. In addition, decisions must be made as to which 4 kHz channel can be disabled during relay operations if it is desired to boost the power output of the relay channel at the time a fault occurs. Aside from these application differences, single-sideband PLC offers the same characteristics as single-function equipment. Note however, that European SSB equipment can generally not be used for phase comparison relaying as the protection channel provides pulse stretching.

PLC Considerations, Capacitor and Reactor Applications

Series capacitors

Series capacitors are installed on long EHV transmission lines to increase power transfer and improve stability due to reduction of line reactance. Even though the negative reactance introduced by the capacitor causes problems for the application of distance protection, any influence on the PLC signal can be ignored.

The capacitor's resistance is negligible and the reactance is very small, even though the capacitor might present a small reactance, rather than capacitance, to high frequency signals.

For series compensated line protection, it is essential that the channel remain operational during all conditions as the protective schemes rely on pilot operation. Distance protection systems often operate as permissive schemes where the loss of a carrier signal will cause time-delayed Zone 2 tripping, which may risk loss of stability. Unblock schemes are therefore preferable. Also, to increase reliability, higher transmit power is often used on series compensated lines due both to the length of the line and that they often are transposed.

Shunt Capacitors

In transmission networks, shunt capacitor banks are installed to control reactive power flow for improved stability and increased power transfer.

When a shunt capacitor bank is located on the transmission line, a *carrier line trap* must be placed on the line side of the bank as the shunt capacitor provides a low resistance path for the carrier frequency signal.

It is generally recommended that shunt capacitors be connected to a substation bus, particularly where a power line carrier communication system will be utilized. If this is not the case, that is the shunt capacitor will be connected so that it is part of a transmission line section, an additional line trap will be required to limit the signal losses resulting from the capacitor installation. The following figure illustrates this application.

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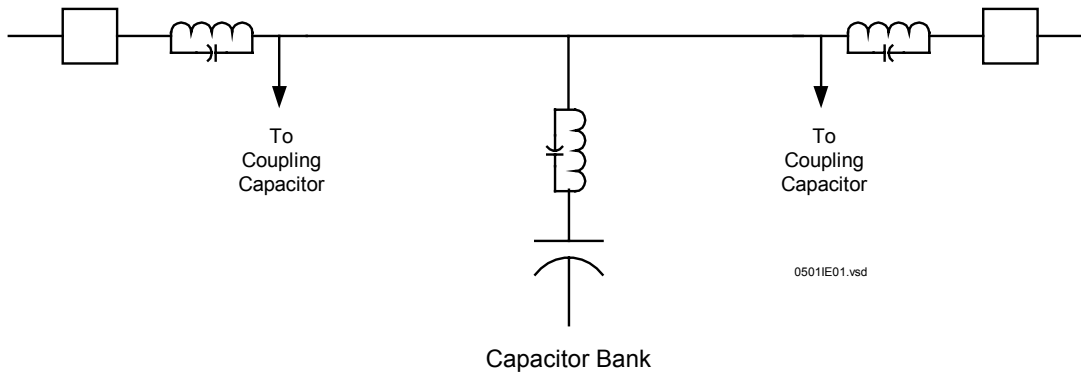


Figure 3 Shunt Capacitor

To trap all three phases may not prove cost effective in all cases, however some consideration should be given to this design. Since PLC is transmitted on all three phases, even though not directly coupled to all three phases, trapping all three phases for line-side capacitor banks may be the only way to adequately transmit the PLC signal.

Shunt capacitor banks are normally switched, that is they may be connected only during certain system conditions. Capacitor switching will often cause transients and overvoltages. However, the switching transients are in the order of 300 Hz – 1000 Hz where they should not interfere with PLC. Overvoltage is limited to 1.1 – 1.4 times nominal system voltage and is therefore of no concern for the PLC equipment.

Shunt reactors

Shunt reactors are used on cables and long transmission lines to compensate for their large line-charging capacitance. Shunt reactors, which can be fixed or switched, vary greatly in size, ranging from 3 to 125 MVA, at voltage levels from 4.6 to 765 kV. Line reactors, which are connected directly or through a disconnect switch, are a part of the transmission circuit.

A shunt reactor, like a power transformer, will look like a capacitance to high frequency signals. When located on the bus side of the line trap, the reactor may need to be considered in shunt loss calculations. If located on the line side of the line trap, the reactor has to be treated as a tapped transformer and might need to be isolated by installing a line trap at the connection point.

Series reactors

Series reactors are used for load regulation by increasing the line reactance. A series reactor, when not by-passed, will act as a line trap for carrier frequency signals. Line trap and coupling capacitor equipment must be applied to the line side of the reactor.

Evaluation of Relay Schemes and Carrier Channel Reliability

Power Line Carrier can be utilized as the communication channel for pilot relay schemes as well as for direct transfer trip applications. The type of carrier channel employed plays an integral part in the reliability of the relay scheme.

Special Considerations in Applying Power Line Carrier for Protective Relaying

Pilot Relay Systems

Pilot relay schemes fall into two basic categories, blocking and permissive schemes. Blocking schemes allow high speed tripping to occur even if the communications channel fails, therefore they favor the dependability component of relay system reliability. Permissive schemes require receipt of the pilot signal to allow tripping; and thus favor the security component of relay system reliability.

Blocking Schemes

Blocking relay schemes typically utilize on-off carrier systems since the pilot signal needs only to be transmitted to block tripping during external fault conditions. The scheme favors dependability since any terminal that sees the fault will trip unless blocked, so failure of the carrier system will not prevent high speed clearing of faults. Because on-off carrier schemes are usually off, the integrity of the communication channel is not known until a fault occurs, and any out-of-zone fault may cause unnecessary tripping of line terminals to occur. This problem can be almost entirely eliminated by installation of automatic checkback equipment that exercises the carrier scheme at regular intervals and will send an alarm if problems are detected. The primary blocking relay schemes that utilize on-off carrier are Directional Comparison Blocking schemes and Single Phase Comparison schemes.

Permissive Schemes

Permissive relay schemes require the receipt of the pilot signal and local protective relay response to allow high speed tripping. These schemes favor security because neither failure of the carrier system nor receipt of an incorrect permissive signal will cause an unwanted trip. The price paid for the increased security of permissive relay schemes is the increased dependency on the communication system to allow high speed clearing. The primary types of permissive relay schemes are Directional Comparison Unblocking, Permissive Overreach Transfer Trip, Permissive Under Reaching Transfer Trip, Dual Phase Comparison, And Segregated Phase Comparison.

Power line carrier is not typically utilized for any of the transfer trip permissive schemes since there is a possibility of the fault disrupting the carrier signal. Such disruption could cause a failure of the pilot trip and slow clearing of the fault. The Directional Comparison and Phase Comparison relay schemes overcome this limitation by utilizing a variant of the transfer trip schemes that is usually called an Unblocking scheme. An Unblocking scheme utilizes frequency shift key (FSK) carrier. The carrier set transmits at what is called the guard frequency under normal conditions and shifts to a trip frequency under fault conditions. Since the guard frequency is continually transmitted, channel integrity is continually monitored and no checkback equipment is required as is the case with on-off carrier. A testing system may be installed that shifts the transmitter from guard to trip, in order to check the shifting periodically. The unblocking carrier schemes utilize special logic that provides a trip output from the carrier set for a short time upon loss of the guard frequency. The trip output logic assumes that the sudden loss of signal has been caused by a fault, and tripping is allowed even with the carrier signal missing. If the loss of signal continues for more than a short period of time (typically 0.5 sec), the carrier set will disable pilot tripping and alarm. The unblocking system thereby provides security on par with other permissive schemes that use communication paths other than power line carrier while providing a level of dependability on loss of channel.

Direct Transfer Trip Schemes

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Unlike either permissive or blocking relay schemes, a direct transfer trip scheme is designed to initiate an unsupervised trip. For that reason, security and dependability of the communication channel are critical. Primary applications are for line relaying utilizing non-permissive under-reach transfer trip schemes, tapped transformers without a local breaker, shunt reactor protection, and breaker failure relaying.

Direct transfer trip schemes use FSK carrier equipment operating with the narrowest bandwidth possible. Although use of narrow bandwidth carrier delays the tripping time, it is more secure than the faster wideband alternative. Dual channel transfer trip schemes are often used to increase system security by requiring the receipt of two trip signals.

Use of Directional Versus Non-Directional Relays for Carrier Start

Directional comparison blocking schemes use a carrier signal to block tripping relays at the remote line terminal for faults external to the line section. Distance relays, instantaneous overcurrent relays, or rate of change detectors may be used to start the carrier transmission. These relays may be directional or non-directional.

Carrier start relays must respond faster than remote tripping relays to insure that a blocking signal has sufficient time to reach the remote line terminal. They should also have a slower dropout rate. Therefore, the carrier start relays have a more sensitive setting than the tripping relays at the remote line terminal.

One advantage of non-directional relays is that they have a faster operating time than directional relays. Faster operating carrier start relays improve system security. Relay system overtrips are more likely to be avoided due to the rapid initiation of the blocking signal. However, non-directional relays start carrier for faults within the line section as well and carrier must be stopped (squelched) for in-line faults by forward-looking directional relays. Overall, system speed is slower if directional relays are used to start carrier. This method increases the scheme's dependability because a forward-looking carrier squelch relay is not required.

Non-directional impedance relays have been used to start the carrier block signal. Care must be taken to insure that the setting does not allow relay pick at normal load levels and thus transmission of a blocking signal for non-fault conditions. In some applications, the carrier start relays are directional impedance relays for phase fault detection, and non-directional instantaneous overcurrent relays for ground fault detection.

“B” Contact Keying and Current Output Interfaces for Directional Comparison

Prior to the implementation of multifunction relays, the traditional method of keying directional comparison relaying (DCR) blocking equipment was by opening a contact, either by removal or by application of voltage from the PLC transmitter.

This configuration allowed the "start" relays to be connected in series to either positive or negative (depending on the equipment used and the connections made). Any of the start relays could initiate the transmission of a carrier block by opening their normally closed "B" contact. Additionally, normally open "A" contacts would be connected in parallel with the PLC input to the keying voltage reference. Any one of these contacts could close, "stopping" the block signal. This allowed a configuration in which "stop override start".

The start string was frequently made up of non-directional relays. Hence, any fault would start the transmission of block. The stop string was made up of directional relays, which would stop the transmission of the block signal if the fault were determined to be in the forward direction. Because of this technique, all faults would initially send a block. A reverse fault would continue

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sending a block while a forward fault would only send a momentary block. Other contacts could stop the block signal if there was a local trip initiation, or breaker failure.

At the receive end, a transistor and dropping resistors developed a current source. This source would be connected to the 85 relay that would open a contact in the overreaching phase and ground relay trip path. The current would also be connected through a relay that could light a receive block lamp, operate an alarm and provide a connection to a fault recorder or oscillograph. Because this was a series string, any break in the string would result in a scheme failure. Testing for proper string integrity is relatively easy.

An external carrier check back device was used to perform a system test of the directional comparison relay scheme. The check back unit would open and close a contact in the send string following a predefined sequence code. A companion unit was located at the remote location. The remote check back would detect this code and respond back. Successful response not only tested the communication equipment but also verified that the keying path was intact. The remote check back monitored the current string. Should a fault occur during the test, the stop would override the start allowing proper operation of the scheme.

There were four main advantages of the "B" contact and current output interface method.

1. The check back device tested the integrity of the keying string as well as the current string. Any open contacts or broken wires would result in a test failure. The problem could be fixed before a scheme misoperation resulted during a system fault.
2. By using a normally energized keying state (de-energize to send block) and a high level of current (generally 200 ma), the scheme offered a high immunity to substation conducted and induced noise.
3. In addition to the coordination time built in or set by the 85 relay, there was an inherent coordination provided by the "B" send contacts and the "A" tripping contacts at the two ends. If the start and tripping relays were matched, the "B" contact would be faster than the "A" contact.
4. Using a "B" contact to operate the keying circuit eliminates the possibility for contact bounce creating carrier holes, which may cause misoperation at the remote end for the external fault.

Present day schemes that use multifunction relays utilize opto-isolator voltage input keying and voltage output interfaces in the PLC. While the speed is about the same as the electro-mechanical equivalents, a broken wire will go undetected until the next system test or a misoperation. When check back devices are used, only the PLC system itself is tested rather than the entire DCR scheme. The opto-isolators can be "turned off" by as little as 4 mA.

During normal conditions, either scheme provides a reliable DCR system. However the "B" contact keying and current output scheme is better suited to predict a failure, prevent a misoperation, and operate properly under noisy substation environments.

Carrier Holes

Various components of the power line carrier System rely on sufficient dielectric strength and isolation from ground. This allows the PLC system to perform properly during ground faults. However, should an insulation breakdown occur, there could be a momentary or permanent interruption in the PLC signal.

Under certain conditions, the breakdown will be voltage dependent, breaking down at the high and low voltage excursions of the fault current, namely in phase with the ground current. A

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digital fault recorder (DFR) connected to monitor the solid state output of the PLC communications receiver may be able to follow this interruption of the signal. Monitoring of the receiver output is frequently done on directional comparison relaying schemes (DCR).

The interruptions in the DCR blocking signal will show up as a series of dashed lines, occurring 120 times per second or twice per cycle. Figure 3 illustrates this point. The lack of a signal where one should appear has been frequently referred to as a carrier hole. If the duration of the hole is sufficient, the DCR scheme will over-trip due to a failure to receive a block at the appropriate moment. When the breakers open, isolating the fault the signal will become constant.

Inspection of Figure 4 reveals that carrier holes occur coincident to the 3I0 ground current, indicating a flashover in the substation. IN2 is the received carrier block signal.

(Note: Due to the sampling resolution of the oscillogram in Figure 4, it appears that the trip output (shown on "OUT 1&2") occurred prior to the loss of block (shown on "IN 1&2"). This sampling jitter would be less evident on recording with a higher sampling rate. Nevertheless, this is representative of the carrier hole phenomena.)

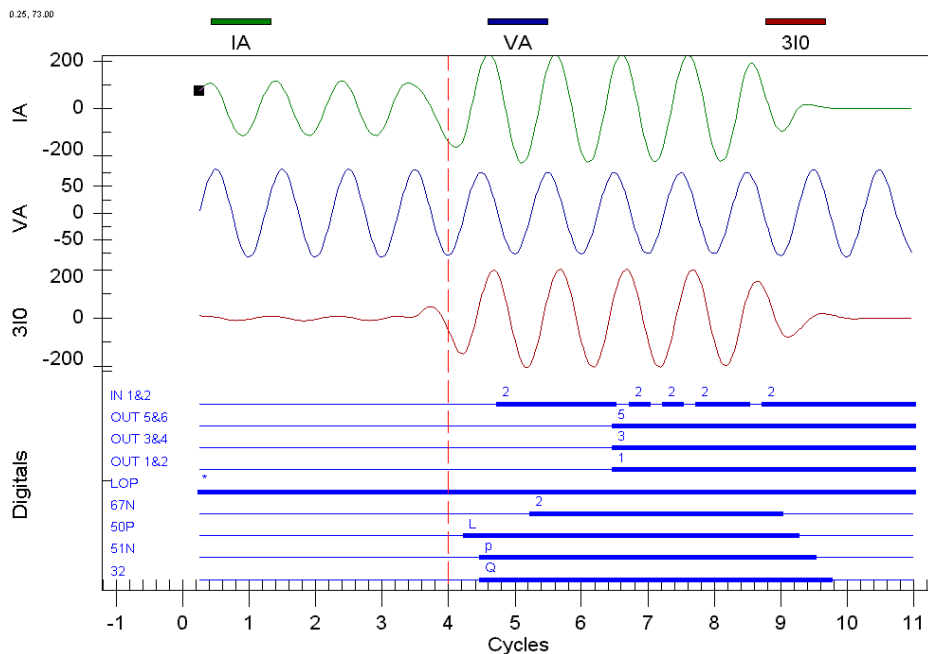


Figure 4 Carrier Holes

Sometimes the carrier holes will only show up on the initial cycles of a fault if the X/R ratio is high enough to provide a large DC offset. This exposes the PLC system to a higher voltage differential. Look for the holes to line up with only the offset part of the ground current and perhaps only on the positive peaks.

Equipment failures associated with the holes may be hard to find. The cause can be at the transmitter or receiver end. Tests can be performed to find the dielectric failure. When doing dielectric tests it is essential that the component under test be isolated from the rest of the system. Appropriate safety measures must be used due to the high voltage conditions prevalent during the test.

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A careful inspection of all coaxial lines is necessary. Generally a 500-volt impedance test is done. The coax should read above 1 meg-ohm sheath to ground with both ends of the cable open. Tuner and coupling cabinets should be inspected for flash over marks. Gaps should be checked for proper clearance. The lead wire between the coupling capacitor and the line tuner should be high-voltage impedance tested. 2500 to 5000 volts is recommended as a test voltage.

An oscilloscope can be connected to the receiver to monitor the magnitude of the 60 Hz component with the equipment off and all components connected normally. The level of the 60 Hz noise should be well under the magnitude of the PLC signal.

Power Line carrier is a very robust communication system. It is not normal for the received signal to be interrupted during fault conditions. Observation and classification of carrier holes followed by an investigation will result in a more reliable protective relaying system.

Carrier Dropout Time Delay

As stated above, a small hole in the carrier signal may lead to a relay system misoperation. This hole could be due to contact bouncing, CCVT transients or the impact of other equipment problems. The time span of typical carrier holes varies from one to three milliseconds. Experience has shown that a time delay of five to six milliseconds will validate if the carrier problem has been caused by a hole or actual loss of signal.

Care must be taken if time delay on drop out is added to the carrier receive circuit to insure that it does not cause problems in coordination with start and stop circuits and current reversal logic. Time delay may mask other communication problems that are likely to cause future carrier failures.

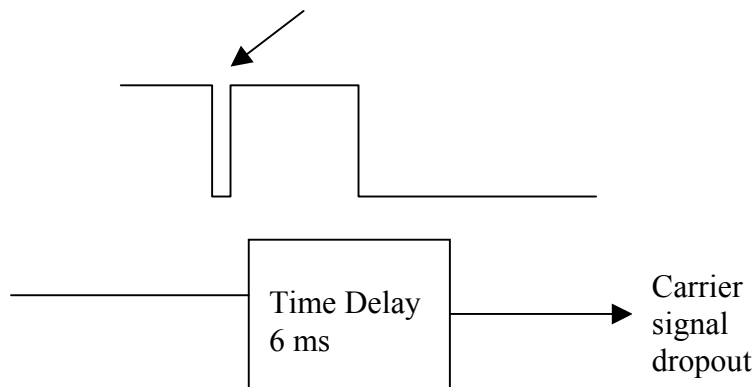


Figure 5 Carrier Dropout Time Delay

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Monitoring Carrier Output

In some older carrier schemes, it is common practice to install carrier signal strength monitoring devices (milliammeter). Typically, this measurement is done at the terminal communication interface point. If external signal monitoring devices are connected, it is important to check the signal strength after installation, as there may be some additional carrier signal loss. Newer communication interface devices have built-in carrier strength (dB) meter integrated into the system.

Phase Identified Transfer Tripping Logic

Description

A number of utilities, particularly in the US and China, have installed parallel EHV lines using double circuit tower construction. This has led to the more frequent occurrence of intercircuit faults and the subsequent over-tripping of lines when a directional comparison scheme with single phase tripping and reclosing is used. The overtripping results when the line protective relaying at one of the ends is unable to identify the proper fault type. To eliminate the overtripping, the line protection schemes have been modified to provide for additional faulted phase information to be transmitted to the other terminal and the modification of the directional comparison scheme logic to interpret this encoded information.

Consider the simple system shown in the diagram below.

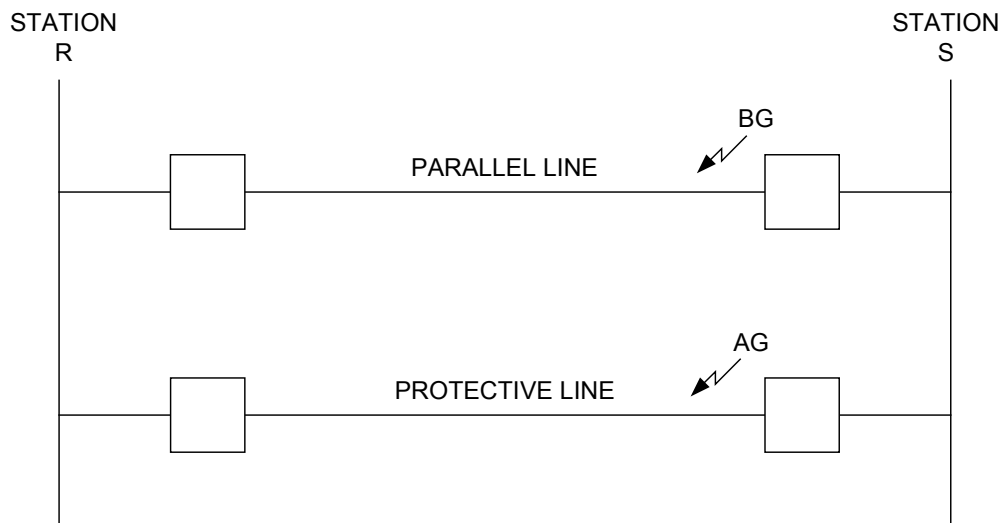


Figure 6 Intercircuit Fault Example

For the fault condition shown, the protective relays on both lines at Station R will detect an AB to ground fault. At Station S, the relay on the protected line will detect an AG fault, while the relay on the parallel line will detect a BG fault. Note that as the fault location is moved away from the bus at station S, the relays at Station R will detect the correct single line to ground fault. If suitable precautions are not taken, the conditions in the example will result in the tripping of all three phases of both lines at Station R, and proper single pole tripping at Station S. The relays at both stations must rely on the local phase selection to determine the fault type and which phase or phases to trip. A correct operation is possible if fault type information from both the

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local and remote ends of the line is used to determine the proper tripping mode. This requires multiple communication channels to transmit the information between the two substations.

If a microwave communication channel is available, then additional communications channels are simply added to the line protection scheme to provide the faulted phase information. However, when power line carrier is the communication channel of choice, the use of three or four channels is not practical due to limited channel availability, bandwidth issues, and additional cost. This has led to the development of a two-channel system designed to encode the faulted phase information. This is described below.

Two-Channel Phase Identified Channel Logic

Pilot Tripping

Typically, the same algorithms found in a conventional distance relay are used to make the local faulted phase determination. The permissive keying is supervised by the fault detecting functions and the local fault type determination algorithm. The channel keying is based on the local fault type as shown in the following table.

LOCAL FAULT TYPE	XMTR #1	XMTR #2
AG, BC, BCG	X	
BG, CA, CAG		X
CG, AB, ABG, 3PH	X	X

Channel Keying for Pilot Tripping (Two Channels)

The receipt of either channel will be used as the permissive signal in the scheme logic. This allows the relay to determine that the fault is within the protected line. In addition to the permissive signal, the receiver inputs will be compared with the selected local fault type per the following table to determine which phase(s) to trip.

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LOCAL FAULT TYPE	RECEIVER	PHASES TO TRIP
AG	RCVR #1·(!RCVR #2)	A
BG	(!RCVR #1)·RCVR #2	B
CG	RCVR #1·RCVR #2	C
AB, ABG, 3PH	RCVR #1·RCVR #2	3 Phase
AB, ABG, 3PH	RCVR #1·(!RCVR #2)	A
AB, ABG, 3PH	(!RCVR #1)·RCVR #2	B
BC, BCG	RCVR #1·(!RCVR #2)	3 Phase
BC, BCG	(!RCVR #1)·RCVR #2	B
BC, BCG	RCVR #1·RCVR #2	C
CA, CAG	(!RCVR #1)·RCVR #2	3 Phase
CA, CAG	RCVR #1·(!RCVR #2)	A
CA, CAG	RCVR #1·RCVR #2	C

Single Pole Phase A Trip Logic

NOTE: Combination of Local Fault type and Receiver not listed in the Table will not allow a permissive trip output.

For the fault conditions shown in the Inter Circuit Fault example diagram, the line relay on the protected line at the Substation S will detect an AG fault and send a Channel 1 signal to the remote terminal. The line relay at Substation R will detect an ABG fault, and will send both Channel 1 and 2 signals to the relay at S. The line relay at Substation S will issue a single pole phase A trip via the operation of the Zone 1 ground distance function. The line relay at Substation R will issue a single pole phase A trip per the logic of Table II (Local fault type is ABG, and only Channel 1 received).

Zone 1 Tripping

Faulted phase determination for Zone 1 tripping is the same as in the existing line relay. This is to allow the Zone 1 elements to maintain their high-speed operation and their independence from the channel.

Repeat (echo) Keying

If no local tripping functions have operated, the repeat keying will be determined by the local fault type determination logic and the received channels as noted below. If any local trip functions have operated, the channel repeat logic will be blocked and the local fault type determination will control the keying outputs. If the fault type cannot be determined locally, the received channel(s) will be repeated as received.

Local Fault Type	Receiver	Repeat Keying
AG	RCVR #1 + RCVR #2	XMTR #1
BG	RCVR #1 + RCVR #2	XMTR #2
CG	RCVR #1 + RCVR #2	XMTR #1·XMTR #2

Repeat Keying Logic

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Non – License of PLC by the Electric Utility

Power Line Carrier and the FCC

The FCC regulates the frequencies used by electric utilities for power line carrier. Part 15 Sections 113 and 217 describe the requirements. These sections are provided below.

FCC Part 15:

Sec.15.113 Power line carrier systems:

Power line carrier systems, as defined in Sec. 15.3(t), are subject only to the following requirements:

(a) A power utility operating a power line carrier system shall submit the details of all existing systems plus any proposed new systems or changes to existing systems to an industry-operated entity as set forth in Sec. 90.63(g) of this chapter. No notification to the FCC is required.

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(b) The operating parameters of a power line carrier system (particularly the frequency) shall be selected to achieve the highest practical degree of compatibility with authorized or licensed users of the radio spectrum. The signals from this operation shall be contained within the frequency band 9 kHz to 490 kHz. A power line carrier system shall operate on an unprotected, non-interference basis in accordance with Sec. 15.5 of this part. If harmful interference occurs, the electric power utility shall discontinue use or adjust its power line carrier operation, as required, to remedy the interference. Particular attention should be paid to the possibility of interference to Loran C operations at 100 kHz.

(c) Power line carrier system apparatus shall be operated with the minimum power possible to accomplish the desired purpose. No equipment authorization is required.

(d) The best engineering principles shall be used in the generation of radio frequency currents by power line carrier systems to guard against harmful interference to authorized radio users, particularly on the fundamental and harmonic frequencies.

(e) Power line carrier system apparatus shall conform to such engineering standards as may be promulgated by the Commission. In addition, such systems should adhere to industry-approved standards designed to enhance the use of power line carrier systems.

(f) The provisions of this section apply only to systems operated by a power utility for general supervision of the power system and do not permit operation on electric lines that connect the distribution substation to the customer or house wiring. Such operation can be conducted under the other provisions of this part.

[54 FR 17714, Apr. 25, 1989; 54 FR 32339, Aug. 7, 1989]

Section 15.217:

Operation in the band 160-190 kHz.

(a) The total input power to the final radio frequency stage (exclusive of filament or heater power) shall not exceed one watt.

(b) The total length of the transmission line, antenna, and ground lead (if used) shall not exceed 15 meters.

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- (c) All emissions below 160 kHz or above 190 kHz shall be attenuated at least 20 dB below the level of the unmodulated carrier. Determination of compliance with the 20-dB attenuation specification may be based on measurements at the intentional radiator's antenna output terminal unless the intentional radiator uses a permanently attached antenna, in which case compliance shall be demonstrated by measuring the radiated emissions.

PLC has served the Utilities well under the rules established by the FCC

The rules established by the FCC may surprise some of the users of PLC. The fact that utilities do not have exclusive use of the band and must not interfere with any of the other users and the fact that any interference to the utility must be tolerated may seem unusual. However this is the general practice for unlicensed FCC governed services covered under FCC part 15. The fact that other users in this band must adhere to restricted power and antenna size guidelines established in section 15.217 has minimized the opportunity for interference to utility operations.

Experimentation and the Amateur Radio Relay League (ARRL):

Many experimenters enjoy operating using the guidelines established within part 15 in the band used for PLC. In October of 1998, the ARRL petitioned the FCC to create a low-frequency Amateur Radio allocation at 135.7 to 137.8 kHz and 160 to 190 kHz. The ARRL proposed permitting CW, SSB, RTTY/data, and image emissions at a maximum power level of 2 W effective isotropic radiated power. This level is much higher than the current level. In addition, as licensed users, Amateurs could interfere with PLC users and be within the FCC regulations.

In May of 2003, the FCC made a ruling to maintain the PLC band in its current state under Part 15 rules. However at the same time they released a Notice of Inquiry for Broadband Power Line Carrier (BPL). BPL is a technique providing high speed broadband over distribution feeders. Speeds have approached 20 mb/s however speeds are considered to be normally less than 2 mb/s.

The FCC inquired if BPL can take the place of PLC. The PSRC provided comments demonstrating that PLC cannot be replaced by BPL.

There is concern among Amateur Radio operators that BPL will radiate harmful noise even if the rules of Part 15 are adhered to. The FCC, in their NOI requested input on changes to Part 15 in both the BPL spectrum and the PLC spectrum. Additionally they requested information regarding the type acceptance BPL and PLC products. PLC products do not currently require any type acceptance.

Frequency Coordination

Since PLC is a non-license use of frequencies, the UTC (United Telecom Council, www.utc.org) maintains a database that documents the use of the PLC frequencies in the United States. The frequencies are submitted by the power utilities with the longitude and latitude information to help coordinate with the use of the spectrum in the PLC range. This database is only available to members of the UTC.

The future:

It is apparent that the FCC and the PLC band must be monitored by the users, namely the protection engineers, to make sure that it remains a viable method to protect power lines.

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(Annex B)

Informative – This is a listing of references on the subject of Power Line Carrier. Should more detail information be required than what is covered in this paper, please refer to the references listed here.

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